Strength and phase of the solar dynamo during the last 12 cycles

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Short title: STRENGTH AND PHASE OF THE SOLAR DYNAMO DURING THE LAST 12 CYCLES

Abstract. We use the *aa* index of geomagnetic activity recorded for 130 years as a proxy for the strength and phase properties of the solar dynamo. To do this we spit the monthly *aa* into two parts; one proportional to the sunspot number and the other the residual. We argue that the first part it is a proxy for the solar toroidal magnetic field. The residual has the same periodicity and closely related amplitude but is shifted in phase. We relate this term to the solar poloidal field generated from the toroidal field in the dynamo process. The changes in both components indicate a long-term trend in the strength and phase of the solar dynamo, perhaps related to 88 year Gleissberg cycle. Our results suggest a change in the distribution of the differential rotation and helicity distribution within the Sun's convection zone over time scales of 50 years.

Introduction

Solar activity is driven by a dynamo operating due to the Sun's convective motions including differential rotation and meridional circulation [*Parker,* 1979; *Zeldovich et al.,* 1983]. Although the solar magnetic field and the law governing the magnetic polarity of sunspots were discovered by G. Hale at the beginning of this century it was not until 1952 that the first observations of the poloidal field were made by H. and W. Babcock. Systematic magnetic observations are available only since 1959 (Mt Wilson Observatory).

The solar dynamo operates by converting a poloidal magnetic field to a toroidal filed and back again. As discussed below, there is a phase lag between the maximum of the toroidal field and the maximum of the poloidal field. *Stix* [1976] showed that in cycle 20 the phase lag between these components was about π. Using measured solar fields we extend this analysis to cycles 21 and 22.

We then suggest a long-term insight into the solar dynamo through an analysis of observations of the geomagnetic activity produced by the solar wind. The solar wind transports magnetic fields from the Sun to the Earth's magnetospheric boundary. The magnetosphere responds to the varying wind by becoming geomagnetically disturbed. These disturbances carry information about the Sun [*Feynman and Crooker,* 1978]. Recently, this point has been stressed by *Lockwood et al.* [1999] and *Wang et al.* [2000] who analyzed the long-term changes in the Sun's open magnetic flux defined by the magnitude of radial component of the interplanetary field.

Solar studies show that active regions are due to the emergence of a deeply-seated toroidal (azimuthal) magnetic field [*Parker,* 1979], and it can be argued that the yearly sunspot number is an indication of the strength of the toroidal field [*Ruzmaikin,* 2000]. Likewise, long-lived coronal holes in the Sun's polar region are a manifestation of the Sun's poloidal field. Just as there are two components of the Sun's field: toroidal and poloidal, so there are two components of fast solar wind: transient and quasi-stationary [*Neugebauer,* 1991], and two components of geomagnetic disturbances; sudden commencement and recurrent storms [*Feynman,* 1986]. We shall show that the toroidal field, transient solar wind and sudden commencement storms are closely related and that the poloidal field, quasi-stationary wind and toroidal fields are also closely related. This allows us to draw inferences concerning the phase and strength of the two components of the solar fields from studying the geomagnetic record.

There is a record of the geomagnetic *aa* index since 1868 [*Mayaud,* 1980]. The *aa* (measured in units of 2 nT) is a mid-latitude range index scaled from two antipodal magnetic observatories. It carries information concerning the disturbances due to coronal mass ejections (CMEs)–which typically produce sudden commencement storms (SCS) in the Earth's magnetosphere – and by quasi-stationary solar wind–which typically causes storms that recur in about 27 days [*Feynman,* 1986].

Figure 1 presents a schematic of relationships between solar and interplanetary fields. When the poloidal field is at its maximum it appears near the poles of the Sun as large slowly changing regions of a single magnetic polarity. High-speed solar wind arises from these regions [*Neugebauer,* 1991], and expands to the equatorial plane where it causes the recurrent magnetic storms. There is another source of the solar wind related to largescale regions of closed magnetic field. Field lines from these regions emerge through the solar surface and re-enter it after extending no more than one or two solar radii above the surface regions [*Neugebauer,* 1991]. These lines are related to the toroidal component of the solar field (see Figure 1). They form magnetic structures that produce CMEs, i.e. transient high speed solar wind [*Neugebauer,* 1991]. The high speed CMEs produce sudden commencement magnetic storms [*Tsurutani et al.,* 1997].

Here we split the *aa* index into two parts: one related to transient geomagnetic storms and associated with the solar toroidal field; and the other related to recurrent magnetic storms and associated with the solar poloidal field. We discuss our results in terms of the strength and phases of the Sun's dynamo.

The two field components generated by solar dynamo

The mean-field dynamo produces a surface magnetic field which (at least its axisymmetric part) is distributed in the form of waves propagating towards the equator with the period of about 22 years [*Parker,* 1979; *Zeldovich et al.,* 1983]. With θ as the co-latitude, the toroidal component, B_T, and the poloidal component, B_p, are non-linear periodical functions:

$$B_T = B_T(k\theta - \omega t), \quad B_p = B_p(k\theta - \omega t + \varphi), \tag{1}$$

where k and ω are the wavenumber and the frequency of the dynamo waves, and φ is the phase shift between the two components. The frequency and phase shift are determined by the two main sources of the field generation: the gradient of the angular velocity (differential rotation) and the strength of the mean helicity of the convective motions.

In a simplified explanation, the phase difference between the components. The differential rotation, with its maximum probably located near the bottom of the convection zone (see below), converts the poloidal field into a toroidal field. The newly born toroidal field diffuses to the source of the helical motions (estimated to maximize in the middle of the convection zone [*Zeldovich et al.,* 1983]) where a renewed poloidal field is generated. The phase shift is proportional to the diffusion time between the sources.

Stix [1976] compared these two components using the butterfly diagram (time-latitude dependence of active region emergence) and photospheric magnetograms during cycle 20 (1965– 1975). The butterfly diagram was used as a proxy for the toroidal field. The line-of-sight magnetograms gave information about the poloidal field. Stix found that the phase difference φ between B_T and B_p was close to π.

We extend this comparison to solar cycles 21, 22 (1976-1999). We use the spherical harmonics of the photospheric magnetic field obtained at the Wilcox Solar Observatory. The poloidal field is represented by the axisymmetric radial component calculated as

$$B_p = \sum_{l=1}^{9} g_l^0 P_l(cos\theta) \tag{2}$$

where g_l^0 are the harmonic coefficients and P_l are the Legendre polynomials. The contours of annually smoothed B_T are plotted in Figure 2, in the upper panel. We are interested in the sign of the field. Red (blue) contours denote positive (negative) fields. In the lower panel, we show the butterfly diagrams (from the web site http://science.msfc.nasa.gov/ssl/pad/solar/sunspots.html), used as proxy for the toroidal magnetic field. The cycle 21 and 22 results for the phase shift of about π, respectively.

Geomagnetic detection of the solar magnetic field

Both aa and the sunspot number W show an 11 year variation, however these variations are not the same [*Feynman,* 1986]. The correlation between W and aa is only 0.47. To understand this we follow the procedure suggested by *Feynman* [1982]. She divided the aa into two parts: one (aa_T) proportional to W and the other (aa_P) defined by

$$aa_P = aa - aa_T. \tag{3}$$

She then demonstrated that aa_T was highly correlated (0.85) with the number of CMEs, which we argue here gives information on B_T. Since the decomposition was made on a strictly formal basis there was no a priori reason that aa_P should have any physical interpretation. However, her analysis of aa_P showed that it was very strongly related to the correlation of aa during one solar rotation with the aa during the next. Hence it represented the activity due to the quasi-steady polar coronal holes, i.e. we can associate aa_P with B_P.

Here we apply the same method to the monthly average aa from 1868 to 1999. First, by plotting aa as a function of the monthly sunspot number we find that all values of aa lie above a minimal line approximated by

$$aa_T = 0.07W + 5.17 \tag{4}$$

which we take as the definition of aa_T. Then aa_P is defined by Eq.(3). The two components of aa are plotted separately in Figure 3.

Using aa_T and aa_P as proxies for the toroidal and poloidal components of the solar magnetic field we examine the amplitude and phase properties of aa_T and aa_P during the last 12 solar cycles. The amplitude has been studied elsewhere [*Feynman and Crooker,* 1978; *Lockwood et al.,* 1999; *Wang et al.,* 2000]. The long-term behavior of both components indicates an increase of the solar wind and solar magnetic field since 1900, in agreement with the 90-year Gleissberg variation. It appears that the present activity is in the declining stage of the Gleissberg cycle. The phase shift between the components is shown in Figure 4 where filtered aa_T and aa_P are plotted together. The cycle by cycle phase shift (defined as the ratio of the time difference between the maxima of aa_P and aa_T normalized by the period of that cycle) is shown in Table 1. The accuracy of the determination can be gauged by comparing with the directly determined results. For cycle 20 the phase shift φ from the aa_T and aa_P analysis (0.9π) is in surprisingly good agreement with the about π found by *Stix* [1976]. For cycles 21 and 22 the phase shift from the aa_T and aa_P analysis can be compared with the phase shift from the solar observations (Figure 2). There is inaccuracy in both methods of determining the phase. "Sunspot maximum" can be defined in various ways (maximum of the monthly average or maximum of the 13 month running averages for example). Each definition will give a somewhat different phase value. Likewise, the maximum of the poloidal fields can not be assigned to accurately specified time, as can be seen from Figure 4. Similarly, the aa_T and aa_P phases depend to some extent on the data processing as well as their strict validity as proxies for B_T and B_P. Thus, from the results for the three cycle for which we have aa_T, aa_P and magnetic observations of the Sun's field, we estimate our accuracy of the phases in Table 1 to be about 0.2.

Discussion

Before discussing the phases shown in Table 1, a comment on the accuracy with which aa is determined is in order. *Mayaud* [1982], who scaled the three hour values of aa from the original magnetograms for the first 100 years of data gives an extensive discussion of the accuracy and homogeneity of the entire data set. The monthly aa is accurate to within about a unit value, therefore uncertainty in the early aa index could hardly make a significant contribution to the uncertainty of the phase.

Adopting an uncertainty estimate of 0.2 for the determination of the phase, we see that there are two classes of phases. The first class consists of values consistent with $3/4\pi$ which is a value that can be expected on the basis of very simplified dynamo models [*Stix,* 1976; *Zeldovich et al.,* 1983] i.e. all cycles from 14 to 22. The first three solar cycles, 11 through 13, are not consistent with $3/4\pi$. Notice in particular the very large difference between the phases in cycles 16,17,18, 19, 20, 21 and 22 (which average 0.8) and cycles 11,12,13,15 (which average 0.2). Since the larger phases belong to the end of the data set, and the smaller cycles belong to the beginning of the data set, we must consider the possibility that these changes in estimated phase reflect real long term changes in the Sun.

As indicated above, the phase shift expected from dynamo theories depends on the distribution of the differential rotation and helicity throughout the convection zone [*Stix,* 1976]. Observationally, the SOHO helioseismic data indicate that the strongest gradients of rotation are now near the bottom of the convection zone [*Kosovichev et al.,* 1997]. But changes in those gradients have been observed over time scales as small as 1.3 years [*Howe et al.*, 2000]. Although these observed changes are very probably too small and too rapid to change the toroidal/poloidal phase difference, their observation opens the door to the idea that there can be other larger changes on longer time scales. The helicity distribution and its evolution deserves a further investigation. We have demonstrated here strong evidence that the distribution of the differential rotation and helicity within the Sun's convection zone undergoes important changes over time scales of 50 years.

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Figure captions

Figure 1. Illustration of how the components of the solar mean magnetic field manifest themselves in the solar wind.

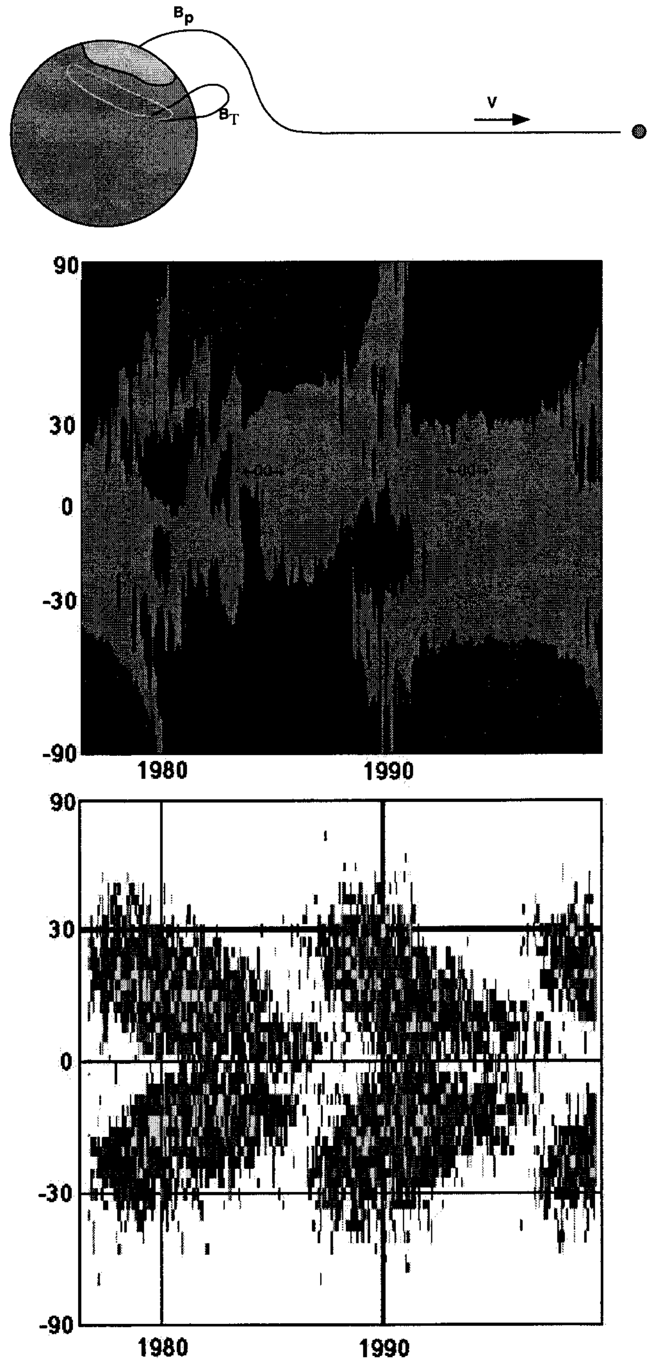
Figure 2. Upper panel. Distribution of the poloidal (radial) component of the photospheric magnetic field. Lower panel. Butterfly diagram as a proxy for the toroidal component of the solar magnetic field. The field in the Northern hemisphere is positive in cycle 21 and negative in cycle 22.

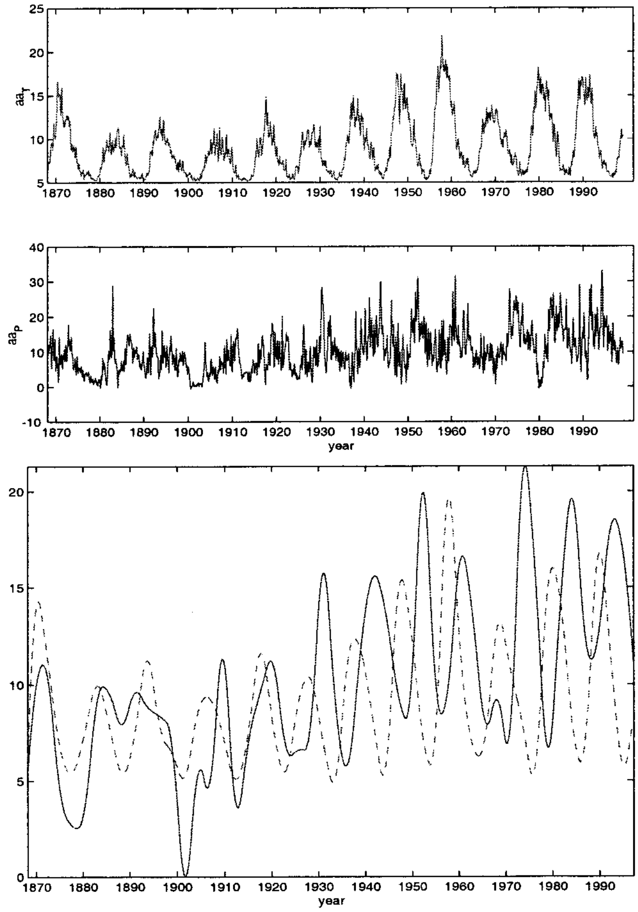
Figure 3. The parts of the aa index associated with the toroidal and poloidal solar magnetic field.

Figure 4. The aa_T (red) component is preceded aa_P (blue) by about 180° at present. This phase shift, however, diminishes back in end of the 19 century.

Table 1. N_c is the cycle number, φ is the phase difference between maxima of aa_P and aa_T.

N_c	11	12	13	14	15	16	17	18	19	20	21	22
φ/π	0.2	0.2	0.2	0.6	0.4	0.7	0.9	0.9	0.5	0.9	0.8	0.6


B_p
B_T
v
90
30
0
-30
-90
1980
1990
90
30
0
-30
-90
1980
1990



aa_T
aa_p
year
year